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## **Keck Adaptive Optics: Wavefront Control Subsystem**

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### **Introduction to adaptive optics at Keck**

Adaptive optics on the Keck 10 meter telescope will provide an unprecedented level of capability in highresolution ground-based astronomical imaging [1,2]. The system is designed to provide near diffraction limited imaging performance with Strehl  $> 0.3$  median Keck seeing of  $r_0 = 25$  cm,  $t_0 = 10$  msec at 500 nm wavelength. The system will be equipped with a 20 watt sodium laser guide star to provide nearly full sky coverage.

The wavefront control subsystem is responsible for wavefront sensing and the control of the tip-tilt and deformable mirrors which actively correct atmospheric turbulence. The spatial sampling interval for the wavefront sensor and deformable mirror is  $d = 0.56$  meters which gives us 349 actuators and 244 subapertures.

The wavefront control design is based on the adaptive optics system operating at Lick Observatory [3]. It uses commercial off the shelf components for wavefront sensing, computer-based control, and for the deformable mirror. The tip-tilt sensor and mirror are custom LLNL designs. In Section 2 we will summarize the wavefront control system design. Section 3 will briefly discuss some of the particular issues in designing a wavefront controller for the Keck Telescope.

### **The wavefront control design**

A block diagram of the Keck wavefront control subsystem is shown in Figure 1. The host computer is a Force SPARC 5 single board based system. Its principal functions are to receive commands from the user interface or supervisory control subsystems [4], to coordinate the actions of the realtime control systems based on these commands, and to transmit telemetry and diagnostic information back to the user interface or supervisory control subsystems.

The two realtime controllers communicate with the SPARC host through the VME-64 bus. On the left in Figure 1 is the tip-tilt control system which is based on a single 68040 processor. On the right is the deformable mirror control system which uses 16 Intel i860 processors to control the 349 actuators.

In laser guide star operations the wavefront tip-tilt from a nearby natural star is sensed with an avalanche photodiode (APD) quadcell. The quadcell is formed by a four lenslet array which is fiber optic coupled to the four EG&G APD photon counting detectors. In natural guidestar operations the tip-tilt is sent to the controller from the wavefront sensor via VME shared memory. Accumulated photon counts or wavefront sensor tip-tilt values are processed by the MVME162 68040-based processor at sample rates up to 1 KHz. The tip-tilt mirror is a 20 cm lightweight silicon carbide mirror.

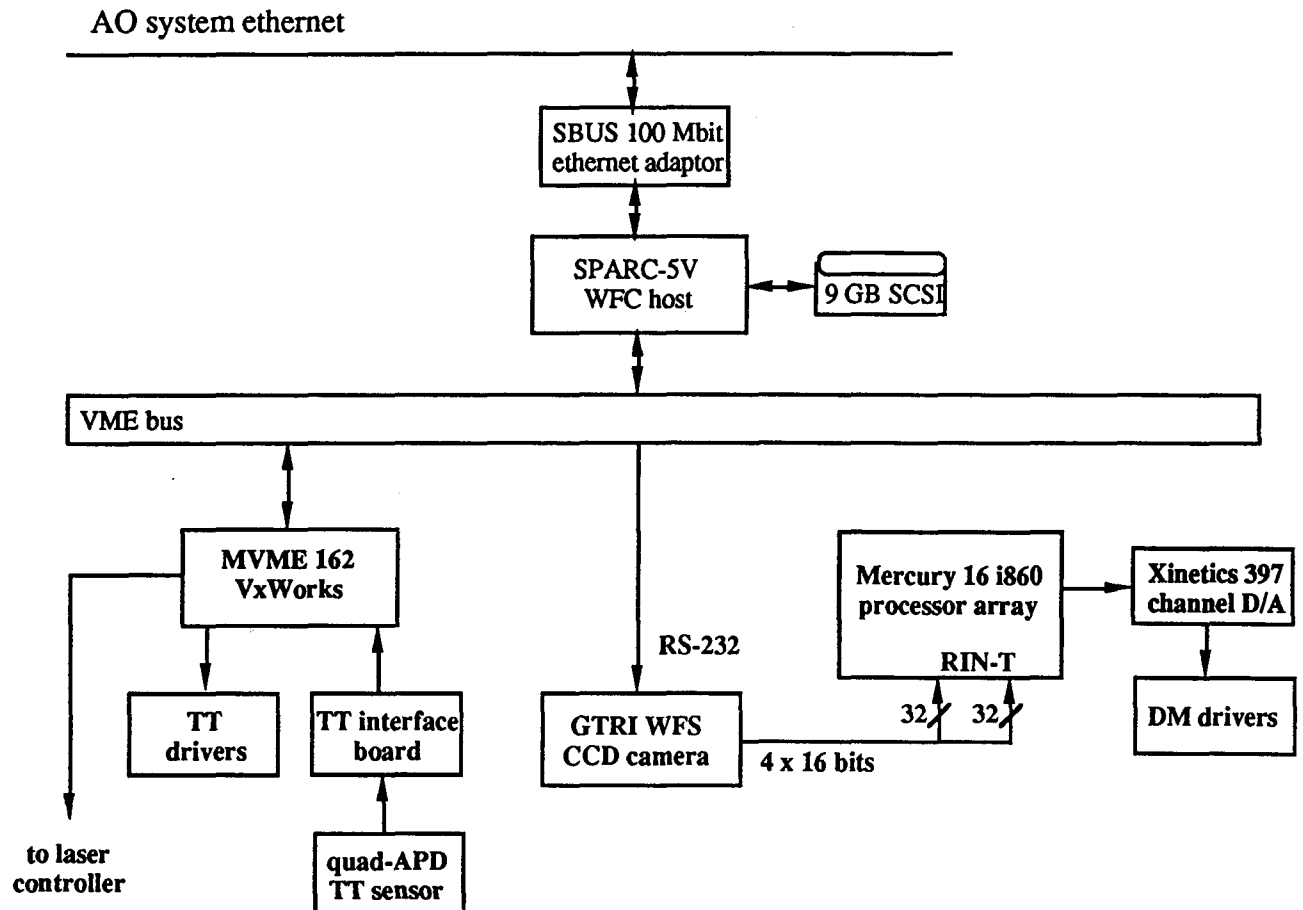


Figure 1. Block diagram of the Keck wavefront control subsystem. The system host and interface to the rest of the adaptive optics system is at the top; the tip-tilt controller and DM controller connect to the host through the VME bus.

High order wavefront errors are measured with a 244 subaperture Hartmann sensor. The wavefront sensor camera was developed by GTRI based on a Lincoln Laboratory 64 x 64 four-port CCD. The CCD has 12 e<sup>-</sup> read noise at a maximum rate of 2000 frames per second. Realtime control of the deformable mirror is based on a Mercury Computer Systems board set with 16 Intel i860 processors connected through a six port high speed crossbar network. The system provides a peak computational rate of up to 1.28 Gflops. The processor array computes image centroids to estimate the wavefront slope,

reconstructs the slopes to give the error wavefront, and performs integral control of the deformable mirror actuators. The total time delay for data transfer and computation is approximately one msec. The Xinetics deformable mirror has a total of 349 PMN actuators. The actuator-subaperture-telescope aperture mapping is shown in Figure 2.

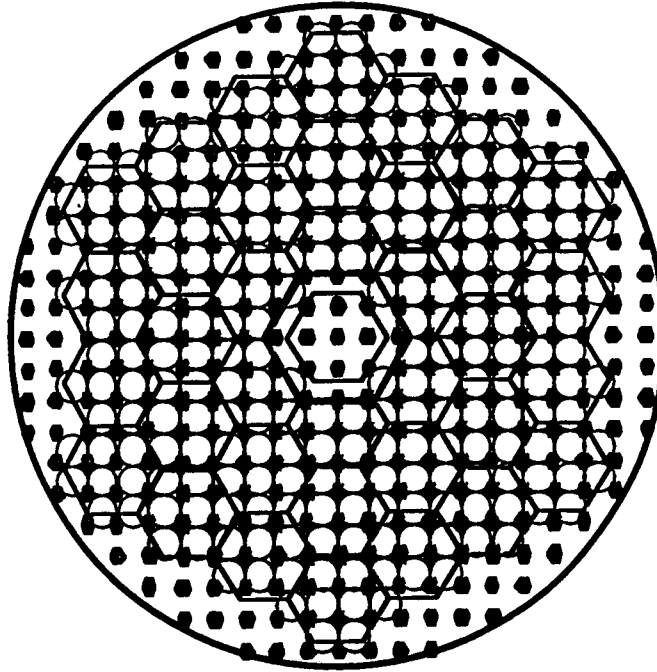


Figure 2. Relationship between the deformable mirror actuators (filled hexagons), wavefront sensor subapertures (open circles), and the segmented ten meter telescope aperture. There are 244 illuminated subapertures in this configuration.

The expected performance of the system was described in [2]. We expect to provide images with  $\text{Strehl} > 0.3$  using a laser guide star reference and a natural guidestar tip-tilt reference with V magnitude  $> 18$ . With a natural guidestar reference for the deformable mirror we should have a limiting magnitude of  $> 10$ . We can optionally reduce the spatial frequency bandpass of the controller to allow operation with a dimmer reference.

### Challenges of wavefront control on the Keck Telescope

The design and performance goals of the Keck adaptive optics system pose several particularly challenging problems. The diffraction limited image cores will range in size from 0.04 to 0.02 arcsec over the specified wavelength range of 1 to 2.2 microns. The small images must not move by more than 10% of their FWHM over exposure times of up to several hours. In addition we expect the tip-tilt sensor to have a limiting V magnitude of greater than 19 and to operate in bright time when the sensor is dominated by moonlit sky background. These performance goals impose severe precision and stability requirements on the tip-tilt sensing and control system.

Because the Keck telescope has an alt-azimuth mount, the pupil image will rotate on the fixed Naismyth platform mounted wavefront sensor and deformable mirror. The main

effect is that wavefront sensor subapertures near the aperture edge will move on and off the illuminated pupil as it rotates. The wavefront controller must adapt for varying illumination in subapertures by updating the weights in the weighted leastsquares wavefront reconstructor as the pupil image rotates.

The goal of developing an astronomical laser guidestar adaptive optics system which is usable in a normal astronomical observing environment poses major challenges throughout the adaptive optics system design. In the wavefront control subsystem a major impact is the need for extensive telemetry and diagnostics. Essentially any signal in the deformable or tip-tilt mirror control processes can be saved and reported to the user interface or supervisory control subsystems. This information can be used to off-load control loops, to monitor the system's operation, or to optimize its performance during extended exposures.

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